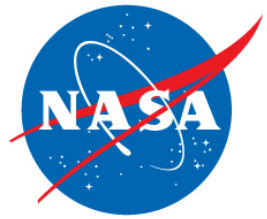# A Sequential Estimation Approach to Determining TRFs

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California Institute of Technology
Pasadena, California, USA

Unified Analysis Workshop

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Paris, France

Introduction

- **Terrestrial Reference Frame (TRF)**
    - The TRF is an accurate, stable set of positions and velocities of reference points on the surface of the Earth
    - The TRF provides the stable coordinate system that allows us to link measurements over space & time for numerous scientific and societal applications including climate & sea level change studies
    - The GNSS, VLBI, SLR, & DORIS geodetic networks, along with ground surveys of stations at co-located sites to tie the networks together, provide the data for determining the TRF as well as for direct science investigations
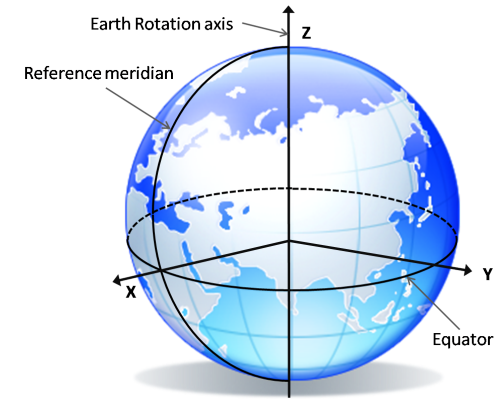
Terrestrial Reference Frame

- **IAG / GGOS goal**

    TRF accurate to better than 1 mm, stable to better than 0.1 mm/yr

- **Pathways to Improving the TRF**
    - Improve analysis of existing ground and space observations (NASA / JPL)
    - Develop next generation ground stations (NASA's Space Geodesy Project)
    - Launch dedicated satellite missions (E-GRASP)

- **NASA/JPL's IERS ITRS Combination Center**
    - Conduct research into improving combined TRFs
        - Sequential estimation (Kalman filter / RTS smoother)
   - TRF represented by time series of smoothed station positions

Sequential Estimation (KALREF)

- Kalman Filter / RTS Smoother
  - Fixed weekly time step
- State vector and full covariance matrix
  - Station positions (weekly)
    - X, Y, Z
  - Earth orientation parameters (daily)
    - Polar motion, polar motion rate, UT1, LOD
  - Helmert transformation parameters (at observation epoch)
    - Translation, rotation, scale (per technique)
  - Parameters of the model of the process (weekly)
    - Linear trend, annual and semiannual periodic terms
- Initialize state at starting epoch
  - Assign large uncertainties to initial state variables
- Propagate state to measurement epoch
  - Using model of process
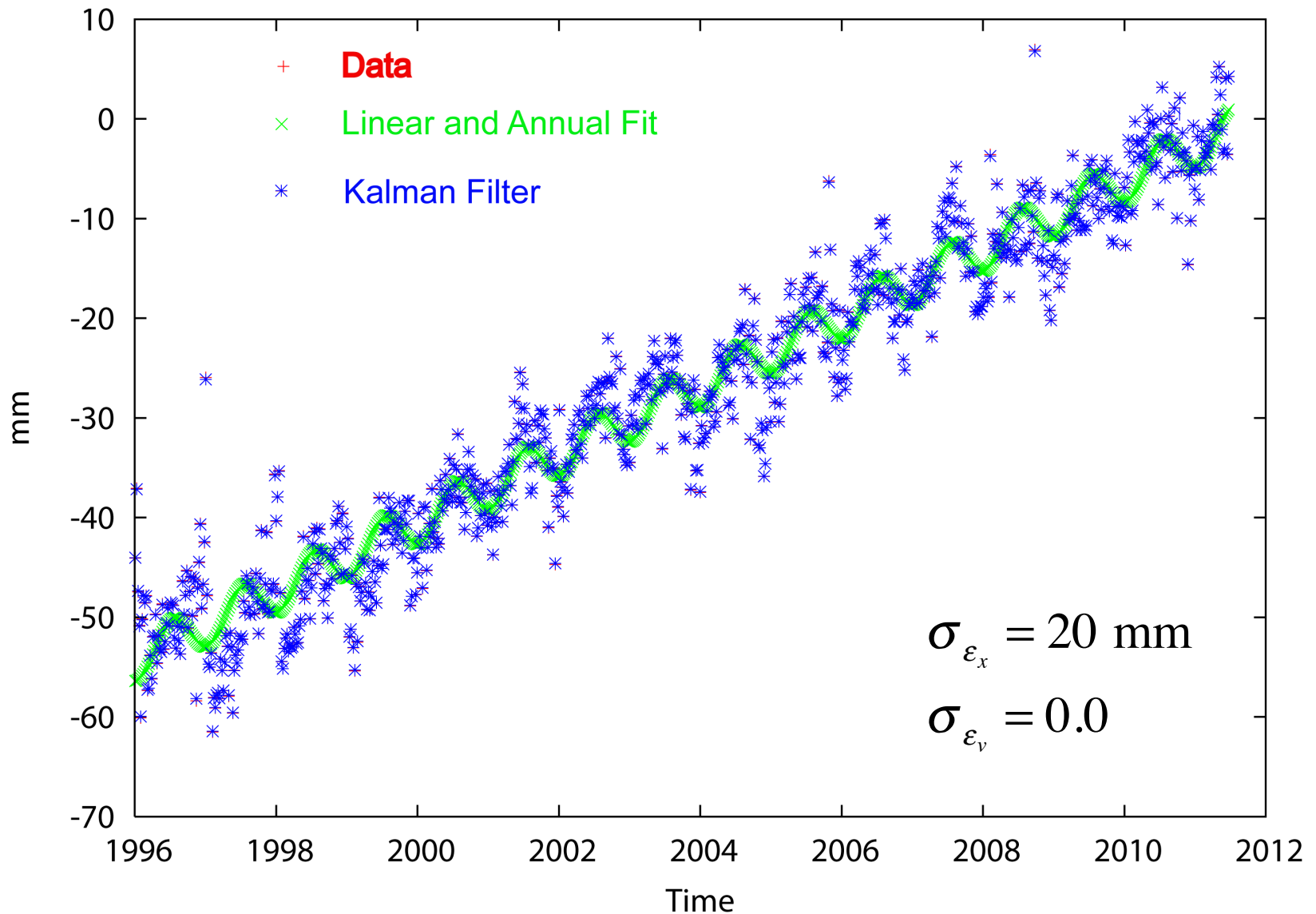- Process noise from surface loading models

Kalman Filter and RTS Smoother

Data

Linear and Annual Fit

Kalman Filter

$$\sigma_{\varepsilon_x} = 0.5 \text{ mm}$$

$$\sigma_{\varepsilon_v} = 0.0$$
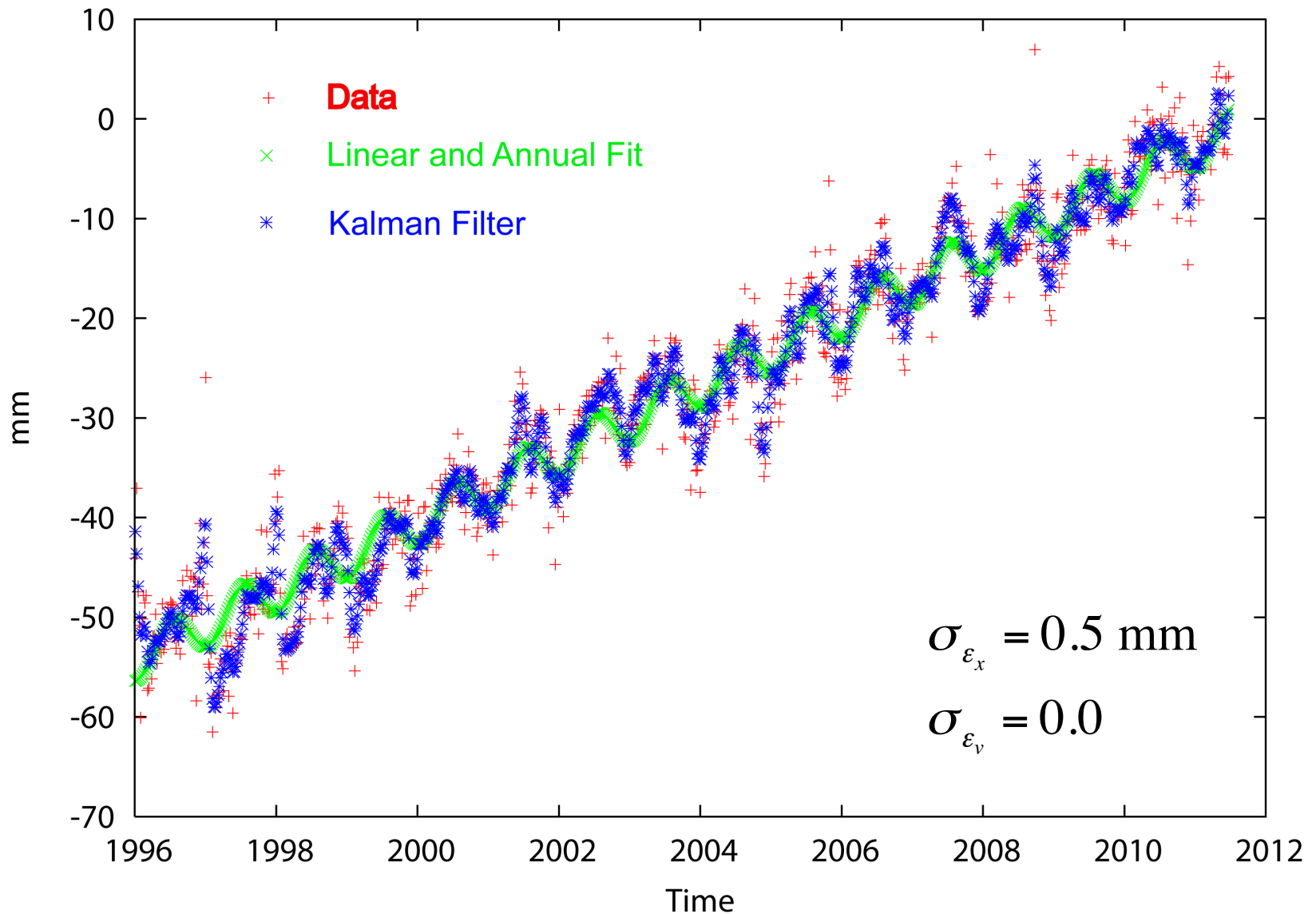
# Kalman Filter and RTS Smoother
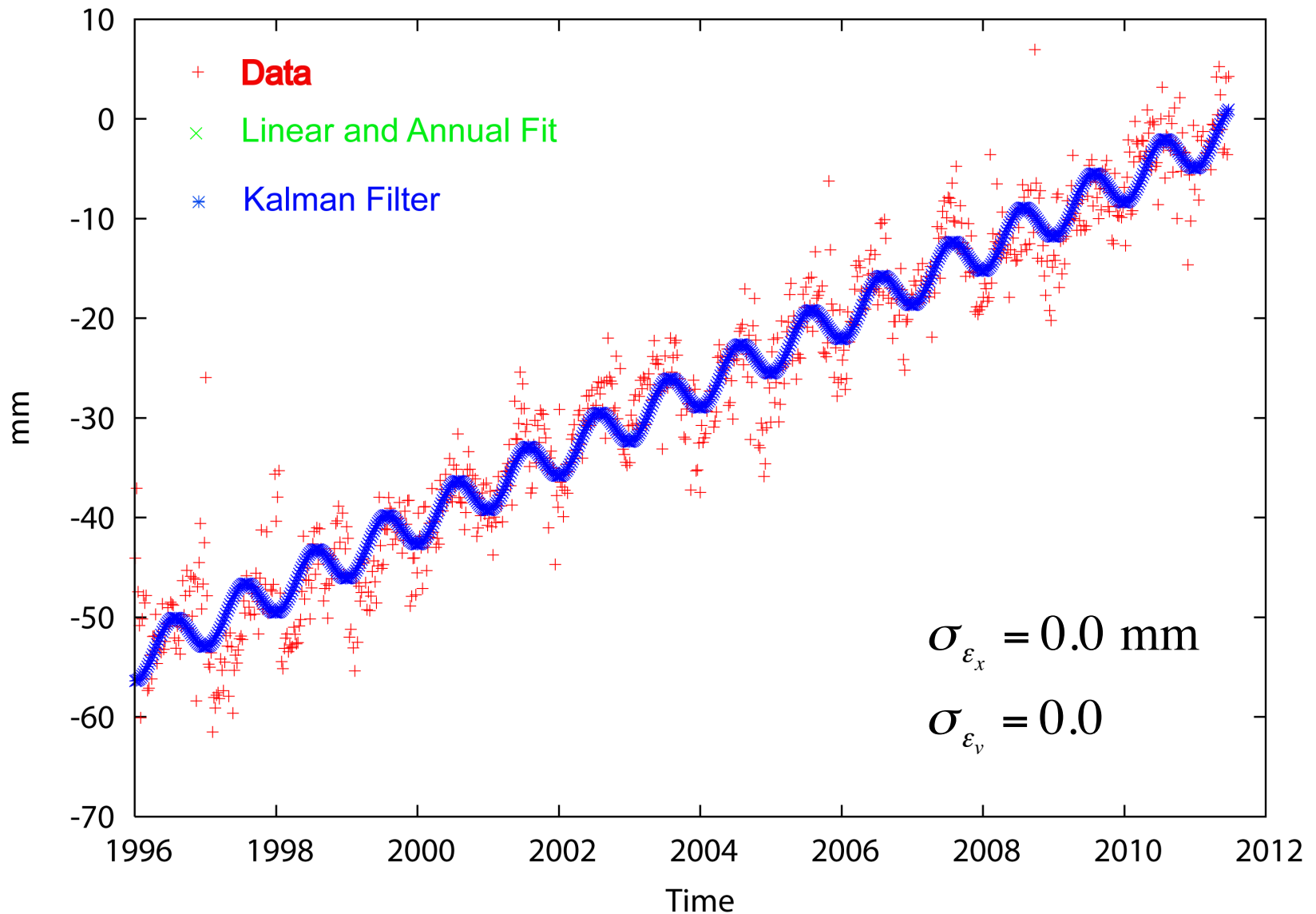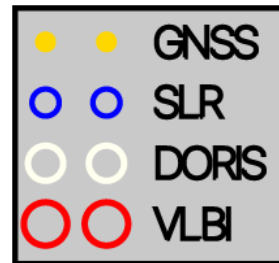
Kalman Filter and RTS Smoother

JTRF2014 Solution Strategy

- **Assimilate and combine**
  - Weekly GNSS, VLBI, SLR and DORIS station positions
  - Daily EOP observations
  - Local tie measurements
- **Kalman filter approach**
  - Realizes a sub-secular frame @ weekly resolution
    - Origin @ quasi-instantaneous center-of-mass (SLR only)
    - Scale is weighted average of VLBI and SLR
    - Orientation defined by convention (no-net-rotation)
    - Local ties applied once
    - Co-motion constraints applied to co-located sites
  - Allows for non-linear motions of geodetic sites (station position process noise)
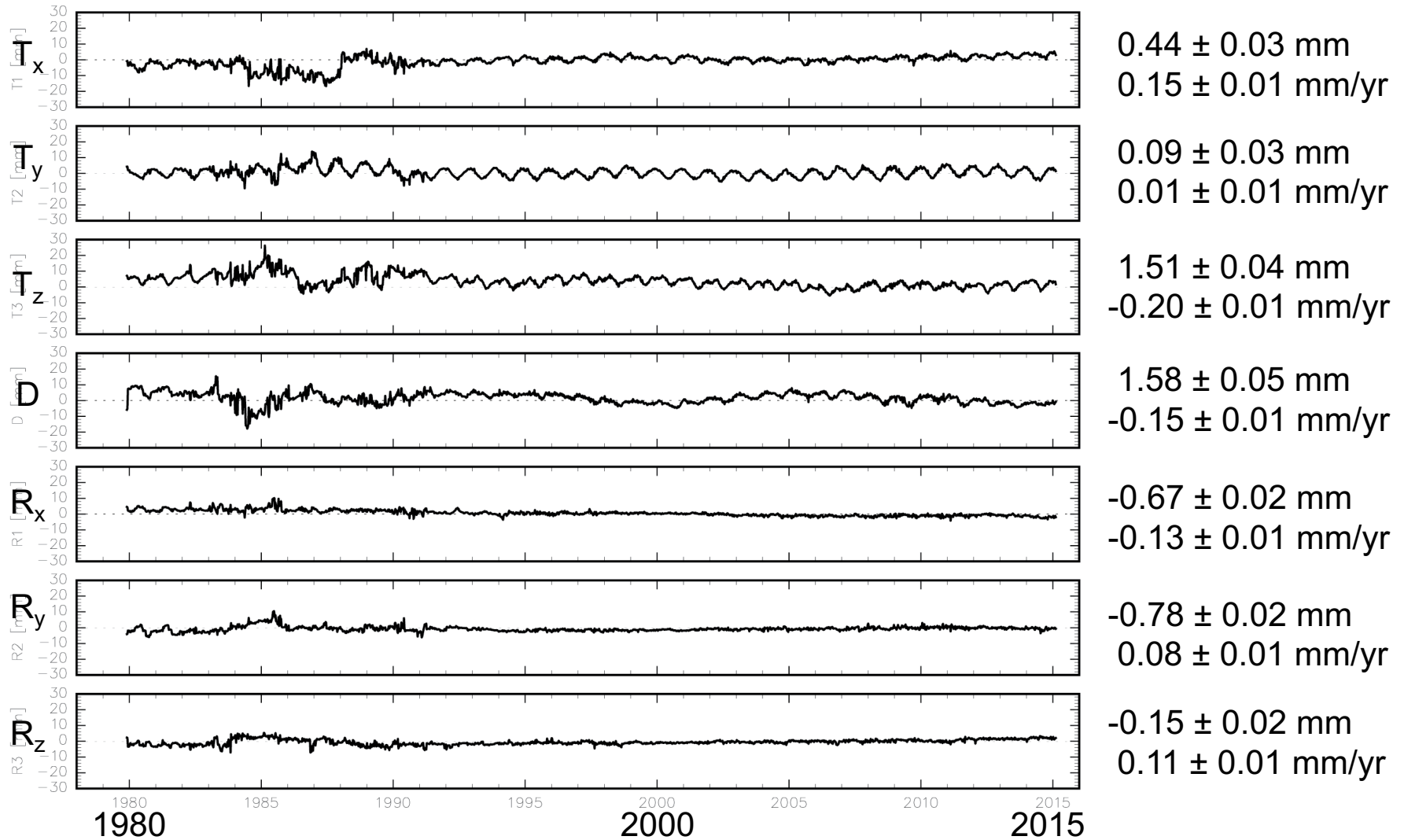
JTRF2014 Station Network
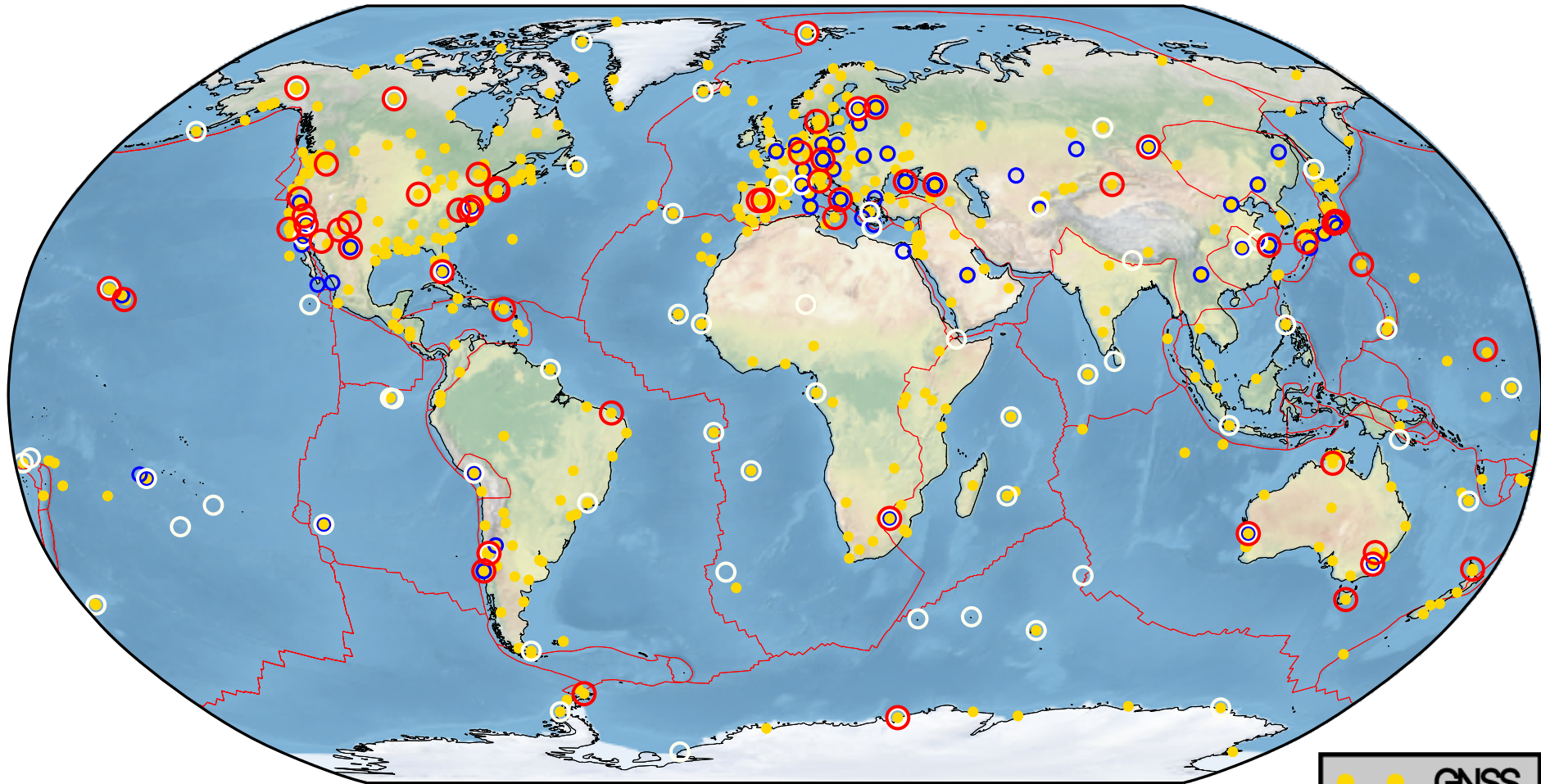
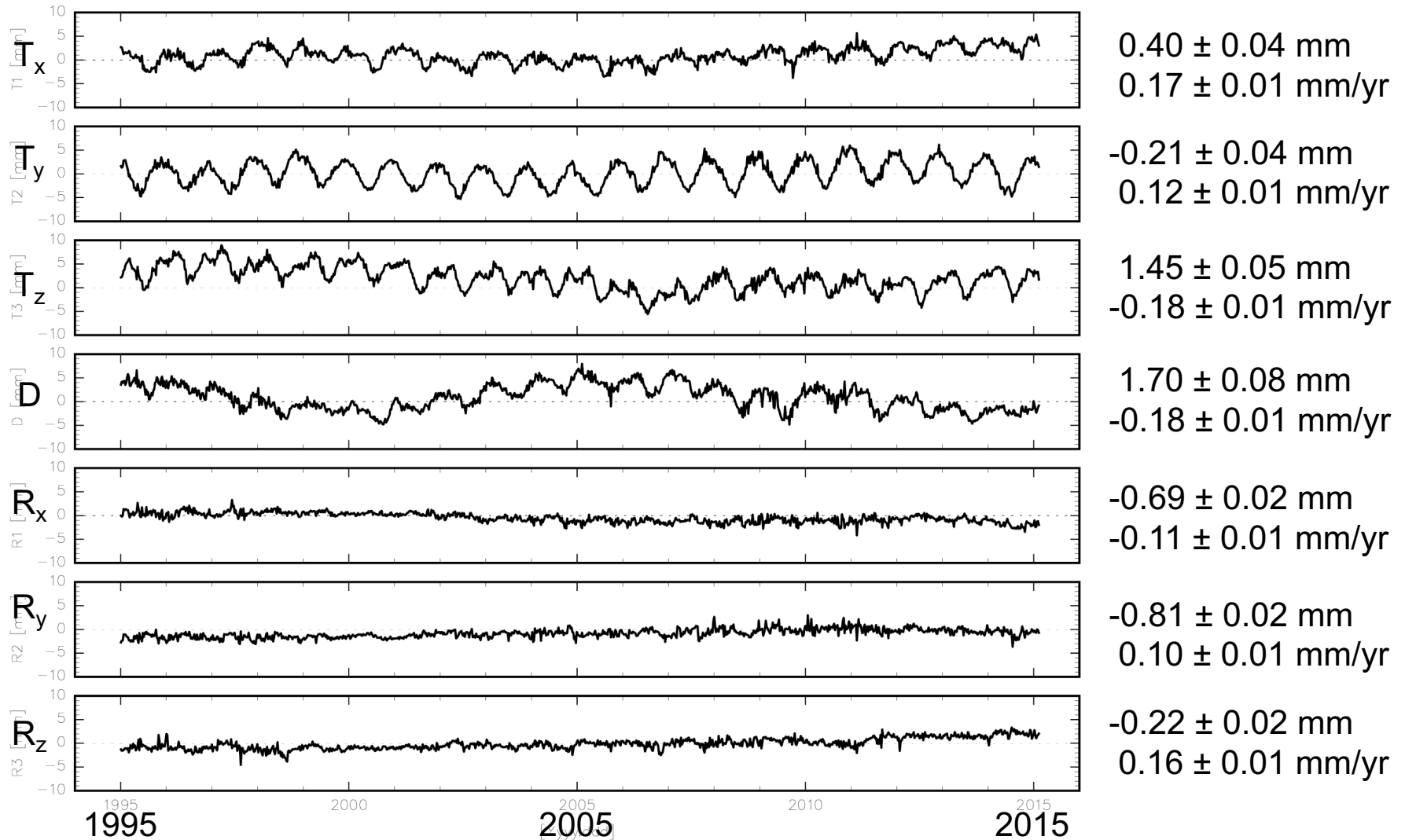671 GNSS   71 VLBI   71 SLR   159 DORIS   972 Total

- GNSS
- SLR
- DORIS
- VLBI

Helmert Transformation Parameters

ITRF2014-JTRF2014 Difference

T_x — 0.44 ± 0.03 mm / 0.15 ± 0.01 mm/yr

T_y — 0.09 ± 0.03 mm / 0.01 ± 0.01 mm/yr

T_z — 1.51 ± 0.04 mm / -0.20 ± 0.01 mm/yr

D — 1.58 ± 0.05 mm / -0.15 ± 0.01 mm/yr

R_x — -0.67 ± 0.02 mm / -0.13 ± 0.01 mm/yr

R_y — -0.78 ± 0.02 mm / 0.08 ± 0.01 mm/yr

R_z — -0.15 ± 0.02 mm / 0.11 ± 0.01 mm/yr

Helmert Transformation Parameters

ITRF2014-JTRF2014 Difference

0.40 ± 0.04 mm
0.17 ± 0.01 mm/yr

-0.21 ± 0.04 mm
0.12 ± 0.01 mm/yr

1.45 ± 0.05 mm
-0.18 ± 0.01 mm/yr

1.70 ± 0.08 mm
-0.18 ± 0.01 mm/yr

-0.69 ± 0.02 mm
-0.11 ± 0.01 mm/yr

-0.81 ± 0.02 mm
0.10 ± 0.01 mm/yr

-0.22 ± 0.02 mm
0.16 ± 0.01 mm/yr

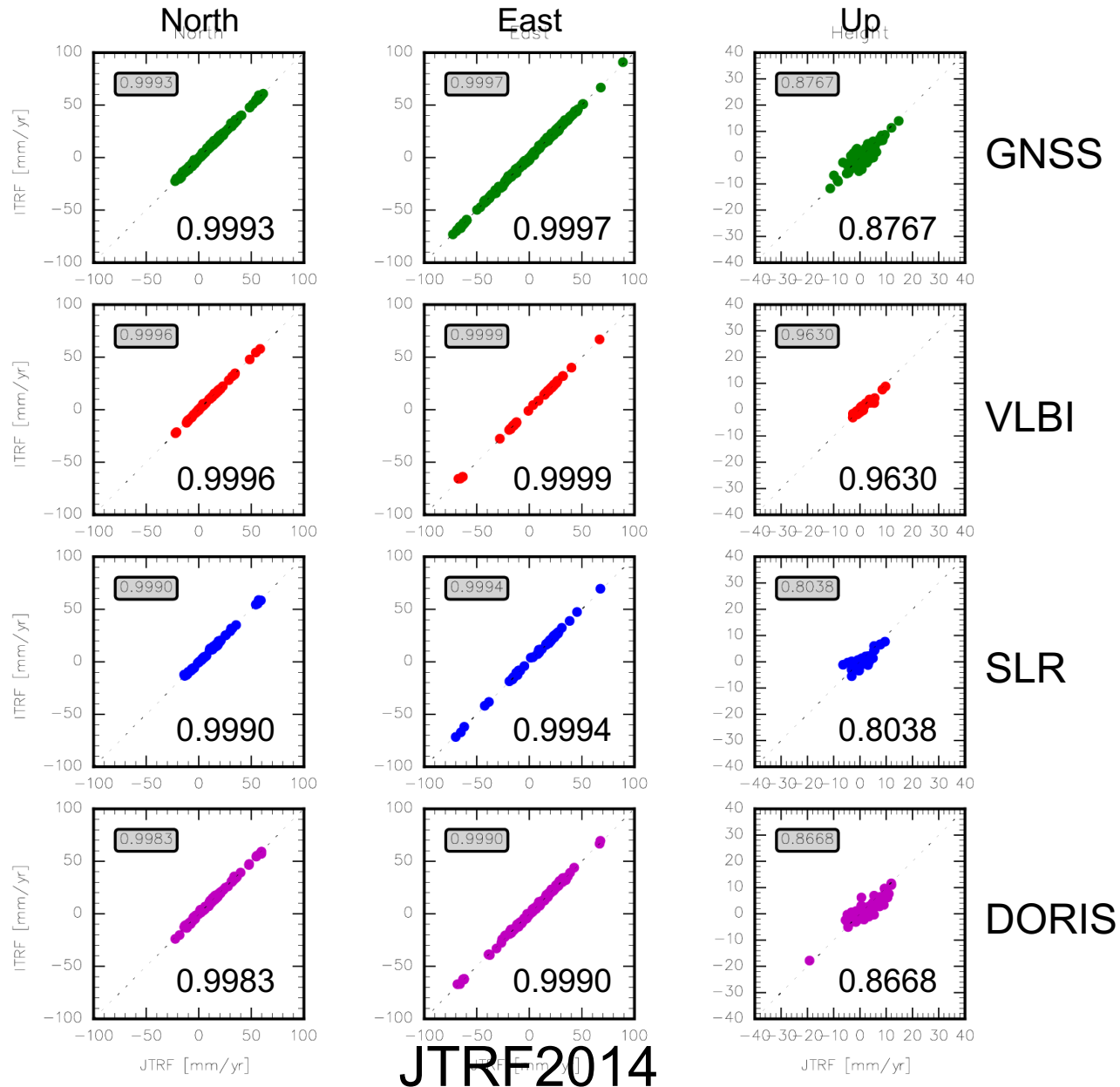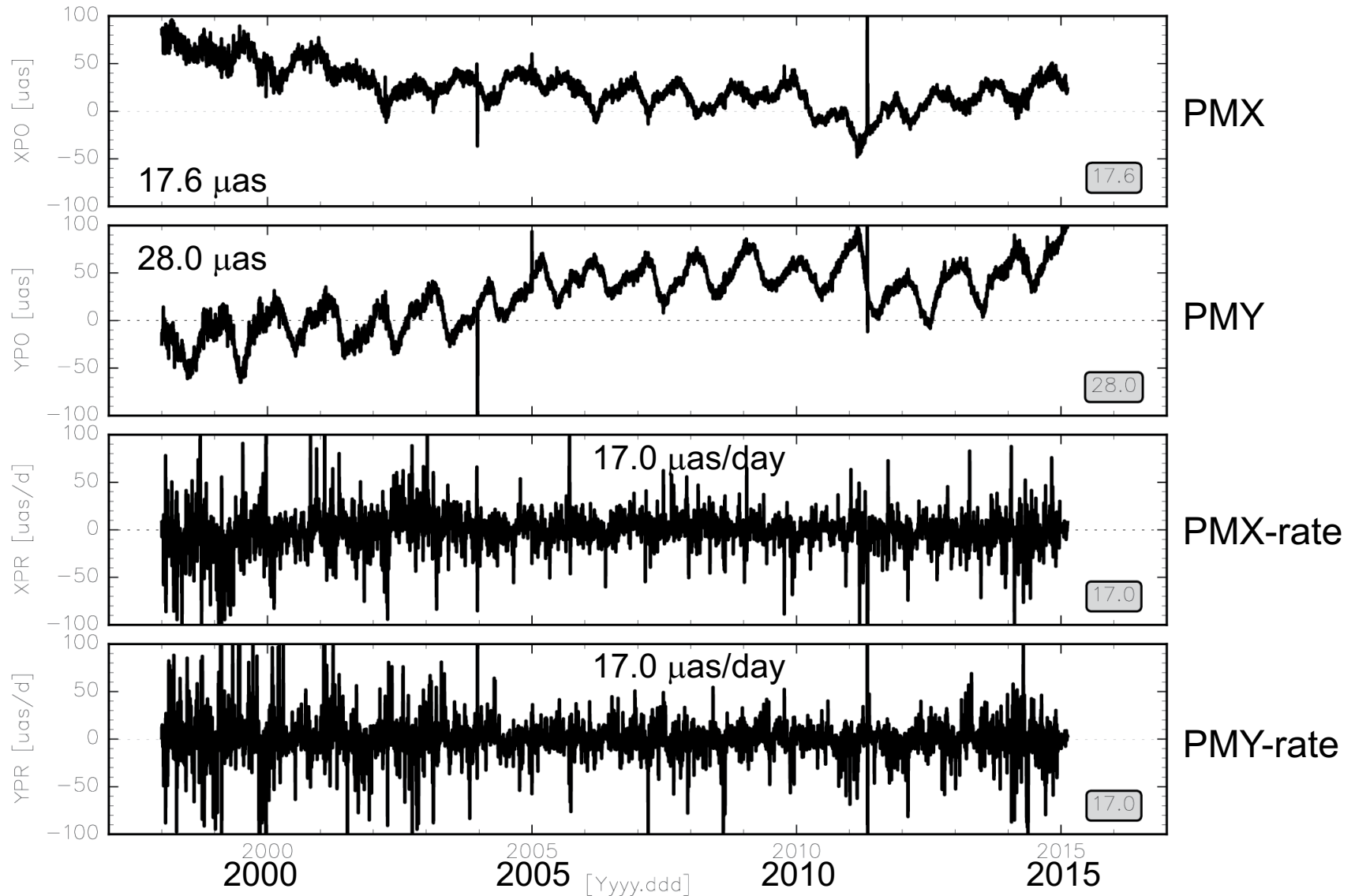# Geocenter
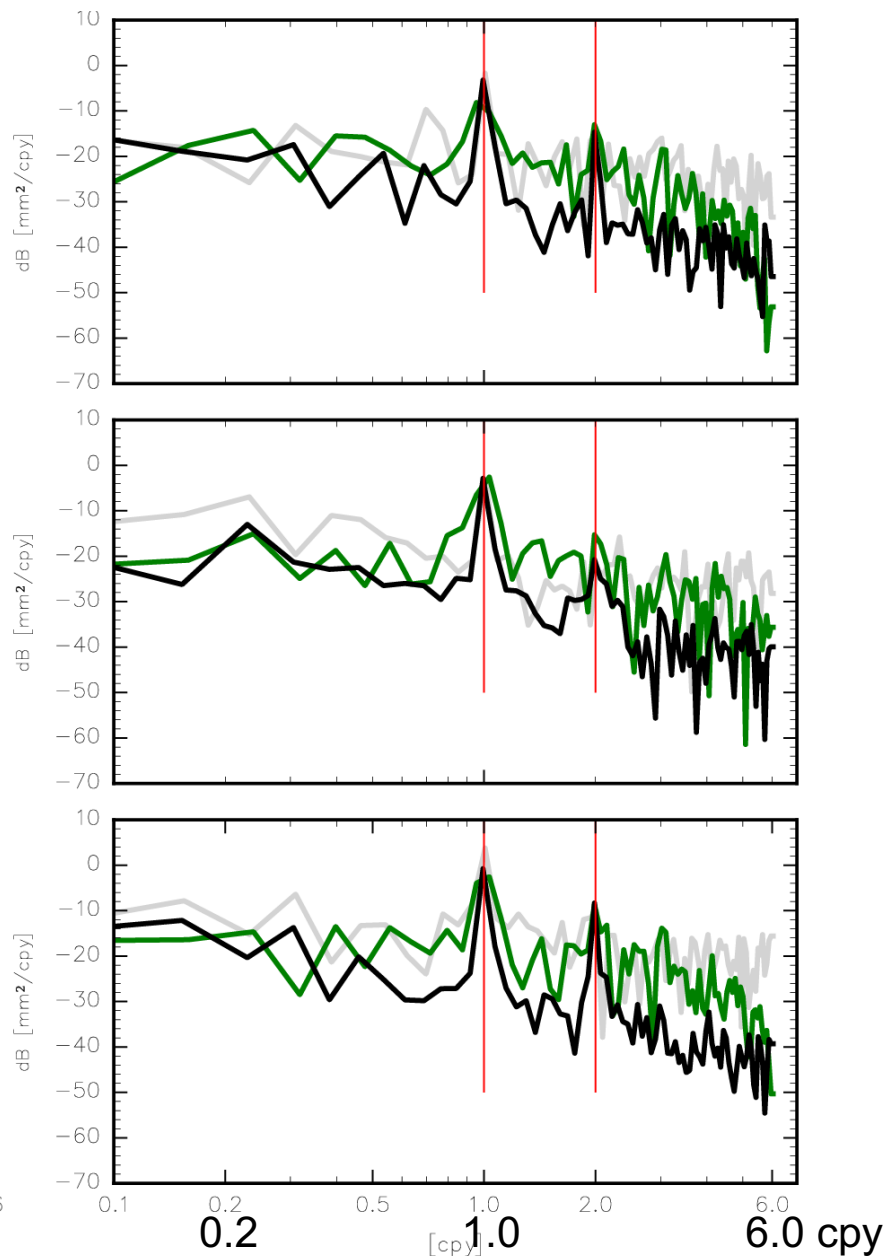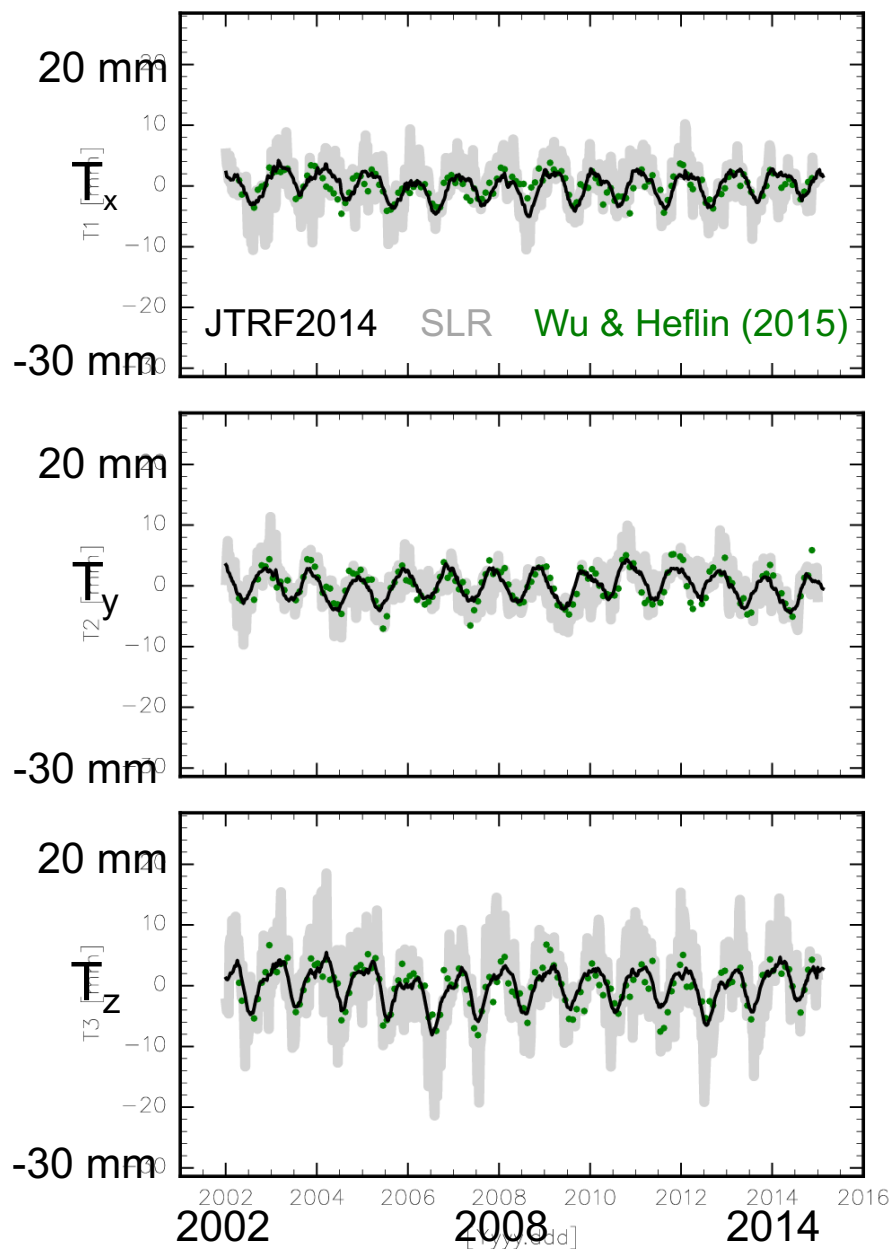
Velocity Fields

Earth Orientation Parameters

ITRF2014-JTRF2014 Difference

Updating TRFs

- ITRFs determined every 3-5 years or so
- Between determinations, model is used to predict positions of stations
  - Accuracy of predictions degrades with increasing lead time
- Can we update TRFs between determinations?
  - Using operational products from Services
    - Not special products produced by the Services for the ITRFs
- In other words, can predictions between frame determinations be constrained by observations as they become available?
- Would still need to predict station positions between updates, so model still needed
  - But updates occur more frequently (monthy?)
  - So prediction interval is shorter & predictions more accurate

Updating JTRF2014

- Save state vector and full covariance matrix at epoch of last measurement
  - Also save ancillary bookkeeping information
- As new observations become available, re-start Kalman filter from saved state
  - Propagate state forward in time assimilating new observations
    - Using RTS smoother
  - Save state at epoch of last new observation
  - Re-generate predictions
  - Repeat at monthly (?) intervals
- Entire history of observations are not processed
  - Only new observations are processed
- Would still want to re-determine ITRFs
  - To incorporate re-processed observations, updated models, ...
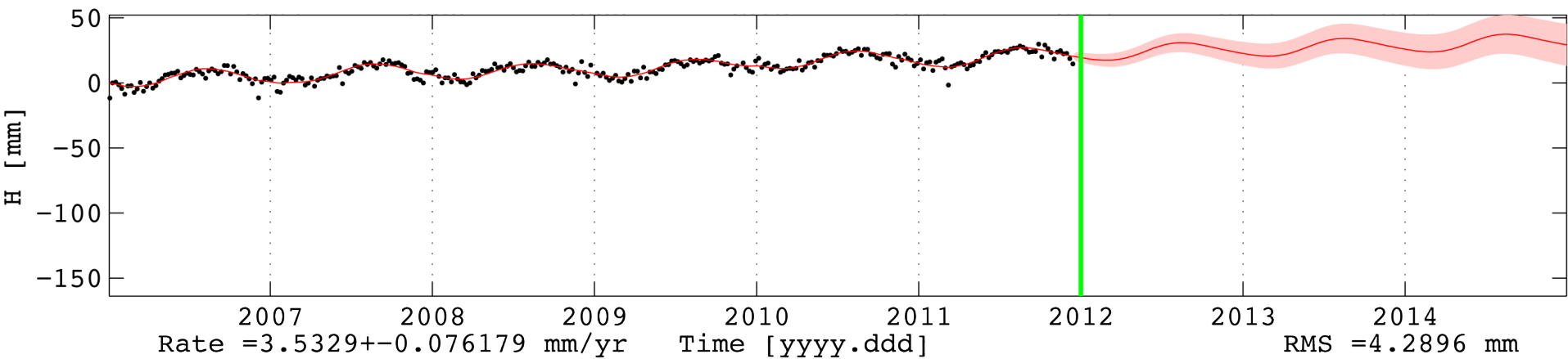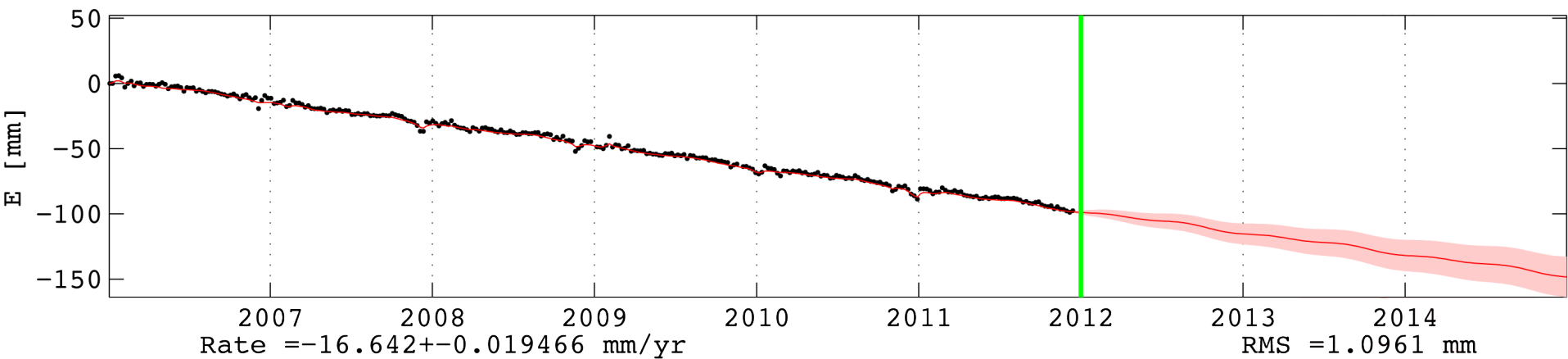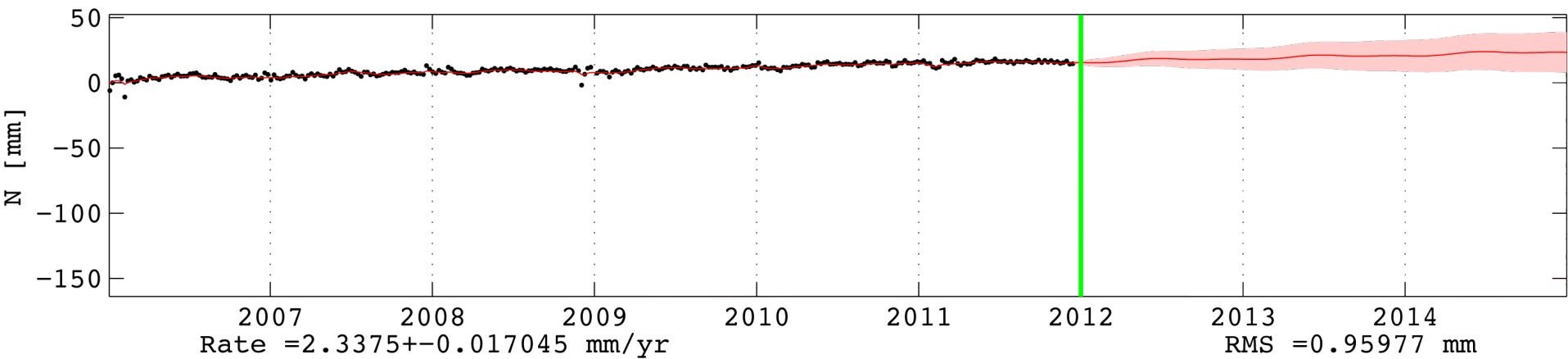 - But perhaps less often than every 3-5 years (?)

Requirements

- Updated TRFs based on operational products
  - Must be able to make operational products consistent with products used to determine the frame being updated
    - Need unconstrained, free network solutions
    - So need to remove constraints applied when generating operational product
    - Need to restore loading displacements if removed
- Ideally, constraint and loading information should be in same SINEX file as observations
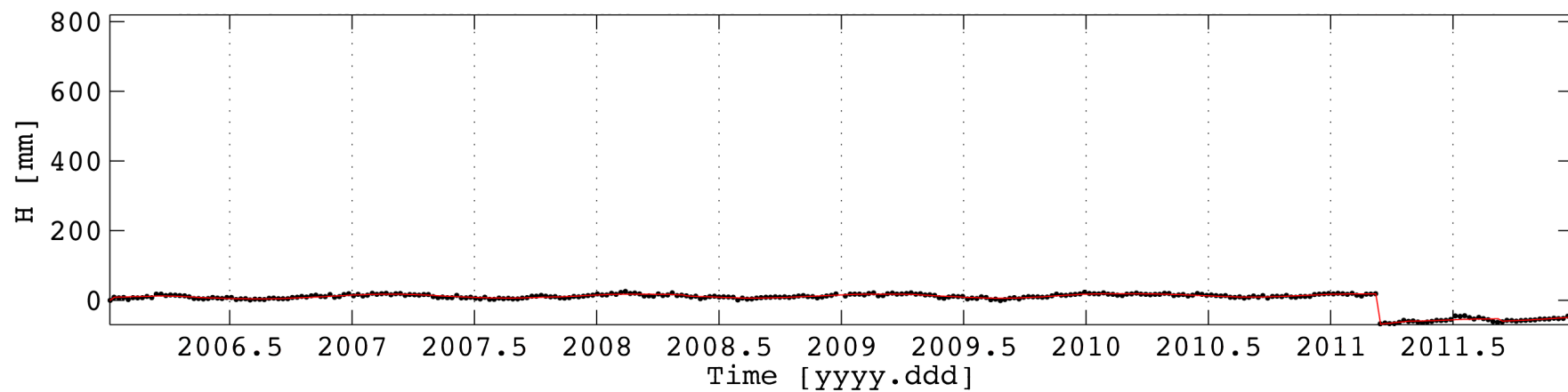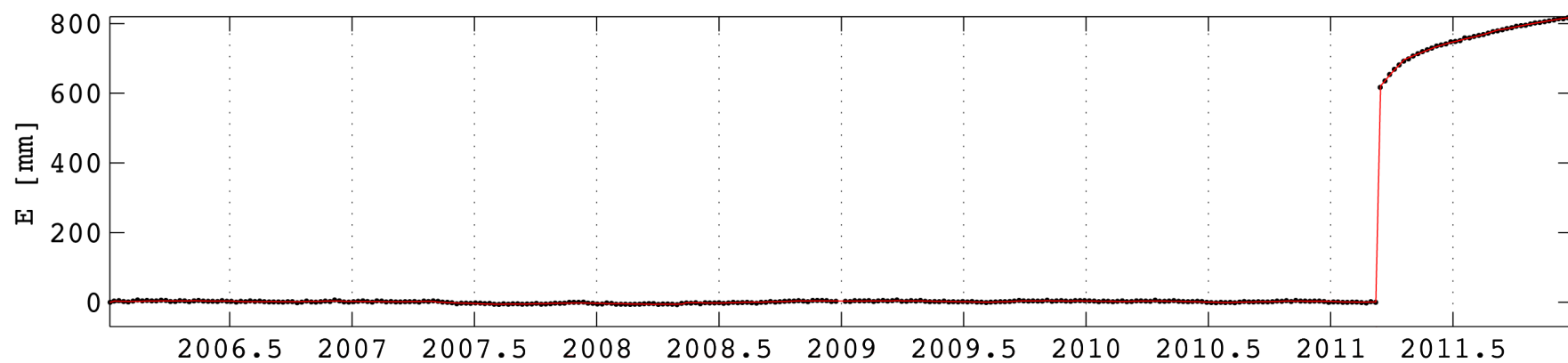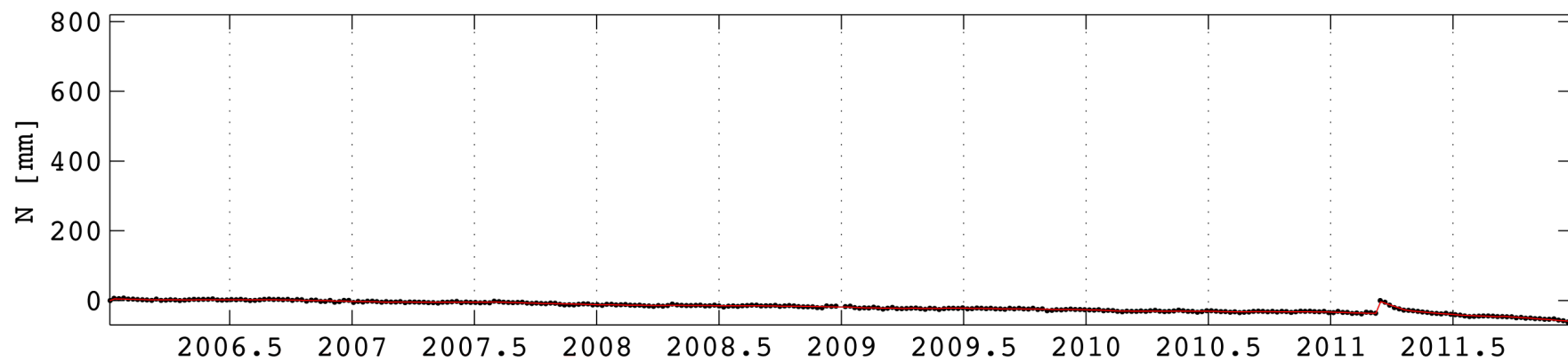 - If not possible, then provide information in separate file

Vinaka
Kiitos
köszönöm
Asante
Shukria
감사합니다
Dankscheen
спасибо
Kam Sah Hammida
Maake
Dhanyavadagalu
ارك ش
Manana
Dankon
Matondo
Terima Kasih
Dank Je
Mauruuru
Biyan
Taiku
Blagodaram
Ngiyabonga
Dziekuje
Chokrane
Arigato
Grazie
Dolci i Chi
Tack
Juspaxar
Thank
Mochchakkeram
Gracias
நன்றி
Bedankt
Dakujem
धन्यवाद
Grazas
You
càm ơn bạn
Kop Khun Khap
Paldies
Tingki
Ua Tsaug Rau Koj
Di Ou Mesi
Kia Ora
Gratias Tibi
Suksama
Děkuji
Nirringrazzjak
Hvala
ありがとう
Obrigado
Matur Nuwun
Rahmat
谢谢
хвала
Welalin
Salamat
Go Raibh Maith Agat
ขอขอบคุณคุณ
Djiere Dieuf
Misaotra
谢
Danke
Merci
Najis Tuke
Eskerrik Asko

Back-up Slides

Time series for ALGO

N [mm]

Rate =2.3375+−0.017045 mm/yr   RMS =0.95977 mm

E [mm]

Rate =−16.642+−0.019466 mm/yr   RMS =1.0961 mm

H [mm]

Rate =3.5329+−0.076179 mm/yr   Time [yyyy.ddd]   RMS =4.2896 mm

Time series for TSKB

Time series for 7345

Rate =−8.7979+−0.14914 mm/yr   WRMS =4.562 mm

Rate =89.0347+−6.7739 mm/yr   WRMS =207.1963 mm